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A method and apparatus relating to microstructured optical fibres

This invention relates to the field of microstructured optical fibres.

In the past few years a new type of optical fibre has been demonstrated, called the photonic crystal fibre (PCF), holey fibre or microstructured fibre [J. C. Knight et al., Optics Letters v. 21 p. 203]. Typically, a microstructured fibre is made from a single solid material such as fused silica glass, within which is embedded an array of holes. Those 'holes' are usually air holes but may alternatively be, for example, regions of a solid material (e.g. silica doped with impurities to change its refractive index). The holes run parallel to the fibre axis and extend the full length of the fibre. A region of solid material between holes, larger than neighbouring such regions, can act as a waveguiding fibre core. Light can be guided in this core in a manner analogous to total-internal-reflection guiding in standard optical fibres. (Standard optical fibres are widely used in applications such as telecommunications. Such fibres are typically made entirely from solid materials such as glass, with each fibre having the same cross-sectional structure along its length. Transparent material in one part (usually the middle) of the cross-section has a higher refractive index than material in the rest of the cross-section and forms an optical core. Light is guided in the optical core by total internal reflection from the material surrounding the core, which forms a cladding region. Most standard fibres are made from fused silica glass, incorporating a controlled concentration of dopant, and have a circular outer boundary typically of diameter 125 microns. Standard fibres can be single-mode or multimode.)

One way to provide such an enlarged solid region in a microstructured fibre with an otherwise periodic array of holes is to omit one or more holes from the structure. However, the array of holes need not be periodic for total-internal-reflection guiding to take place (we may nevertheless refer to such a fibre as a photonic-crystal fibre).

Another mechanism for guiding light in microstructured fibres is based on photonic bandgap effects rather than total internal reflection. For example, light can be confined inside a hollow core (an enlarged air hole) by a suitably-designed array of smaller holes surrounding the core [R. F. Cregan *et al.*, Science v. 285 p. 1537]. True guidance in a hollow core is not possible at all using total internal reflection.

Microstructured fibres can be fabricated by stacking glass elements (rods and tubes) on a macroscopic scale to form a bundle having the required pattern and shape, and holding them in place while fusing them together. This primary preform can then be drawn into a fibre, using the same type of fibre-drawing tower that is used to draw standard fibre from a standard-fibre preform. The primary preform can, for example, be formed from fused silica elements with a diameter of about 0.8 mm.

Typically, single-mode fibre can in fact support two transverse modes, differing in the polarisation direction of the light they contain. The two modes correspond to light having two orthogonal polarisations. In a birefringent optical fibre, the two modes travel at different speeds along the fibre. Microstructured fibres may be made strongly birefringent (see for example, International Patent Application No. PCT/GB00/00600 (The University of Bath)). However, even a microstructured fibre that has had no structures deliberately introduced to enhance its birefringence, yet subject to normal manufacturing

imperfections, typically exhibits much stronger birefringence than a standard fibre, as a result of the much higher index contrast in the microstructured fibre.

For some applications, the strong intrinsic birefringence of a microstructured fibre is desirable. However, for some applications it would be advantageous for a microstructured fibre to exhibit reduced birefringence or even no birefringence. For other applications, it would be advantageous for the orientation of the polarisation axes of the fibre to be readily controllable.

An object of the invention is to provide a microstructured optical fibre having such advantageous polarisation properties.

According to the invention there is provided a microstructured optical fibre comprising a core region and a cladding region, the cladding region comprising a plurality of structures, which have a first refractive index and are embedded in a solid matrix material having a second, different, refractive index, characterised in that the structures are helical along the fibre.

Thus, in contrast to prior-art microstructured fibres, which comprise a plurality of elongate structures running parallel to a longitudinal axis of the fibre, in the fibre of the invention the structures are helical about that axis. The properties of a fibre having such helical structures is dependent upon the period of the helices. (A helix, viewed from the side, is sinusoidal and therefore has an identifiable period. It will readily be understood that, for example, a fibre produced by drawing at a draw speed of 1 ms^{-1} and a spinning rotation of 1 revolution per second produces a helical structure of 1 revolution per meter (that is, a structure having a period of 1 m).) Preferably, the period of the helices is constant along the length of the fibre. Alternatively, the period of the helices may vary along the length of the fibre, in which case the

polarisation properties of the fibre may change along the fibre's length.

Preferably, the helices extend for at least one full period along the fibre. More preferably, the helices extend for a plurality of full periods along the fibre. Still more preferably, the helices extend along the full length of the fibre.

Preferably, the helical structures rotate in the same sense along their full length. Alternatively, the sense of rotation of the helical structures may alternate in successive regions along the fibre. Thus, for example, the structures may initially be helical in a clockwise sense, then straighten out and then become helical in an anti-clockwise sense.

The helical structures may form a rocking filter, in which case the structures will be a plurality of short helices, successive ones of which rotate in opposite senses. Preferably, the period of each of the helices is at least approximately equal to one half of the beat length of the fibre. Such a rocking filter may be made, for example, by rotating the fibre alternately in opposite senses as the fibre is drawn from a preform.

If the helical structures were not helical but extended parallel to the longitudinal axis of the fibre, as in a prior art fibre, the fibre would have a characteristic beat length between its fast and slow polarisation modes, the value of which would depend upon parameters of the particular fibre [Barlow *et al*, Appl. Opt. 20, p.2962 (1981) and Barlow *et al*, Electron. Lett. 17, p. 725 (1981)]. If the period of the helix of the helical structures is much shorter than that beat length then the polarisation modes will be coupled to each other. Preferably, the helical structures have a period that is sufficiently short that a birefringence effect (such as phase birefringence, differential group delay (DGD) or polarisation mode

dispersion (PMD)) in the fibre is reduced. Preferably, the helical structures have a period that is sufficiently short that, in use, polarisation modes of light guided in the fibre are strongly coupled to each other. More preferably, the helical structures are sufficiently short that the fibre exhibits a birefringence of less than half than it would exhibit if it were not spun. Still more preferably, the helical structures have a period that is sufficiently short that the fibre exhibits substantially no birefringence effects.

Alternatively, if the period of the helical structures is much longer than that beat length then the microstructured fibre will be birefringent. The rotation of the structures about the axis of the helix will cause the polarisation axes of the fibre to rotate along the length of the fibre. The helical structures may have a period that is sufficiently long that there is substantially no coupling between polarisation modes of the fibre. Preferably, the helical structures have a period that is sufficiently long that light may pass adiabatically along the fibre as the polarisation axes rotate.

Alternatively, the period of the helical structures may be of a similar length to the beat length; such an arrangement gives elliptical birefringence.

An adiabatic decrease in the period of the helices, for example from infinity (i.e. a region of the fibre in which the structures are not helical but rather extend parallel to the fibre axis) to a length very much shorter than the beat length of the fibre, may be used to provide a stable, broadband linear-to-circular polarisation converter.

The helical structures may be continuous or discontinuous along the length of the fibre. Preferably, the helical structures are regions of a dielectric material that extend unbroken along their respective helices for at least one period of the helical structure. More preferably,

the regions of the dielectric material extend unbroken along the length of the fibre.

Alternatively, the helical structures may be regions of a dielectric material that are discontinuous along their respective helices; thus, the structures may comprise a plurality of bubble-like structures distributed along helical paths. Preferably, the regions of the dielectric material are discontinuous within one period of the helical structure. Such an arrangement may be advantageous in enhancing coupling between polarisation modes. Preferably, the regions of the dielectric material are of a length that is less than ten times their diameter. More preferably, the regions of the dielectric material are of a length that is of the same order of magnitude as their diameter. The regions of the dielectric material may be at least approximately of the same length as their diameter.

Also according to the invention there is provided a method of manufacturing a microstructured optical fibre, comprising: (i) forming a preform arranged to form a core region and a cladding region in the fibre, the cladding region comprising a plurality of structures having a first refractive index and embedded in a solid matrix material having a second refractive index; (ii) heating the preform; and (iii) drawing the fibre from the preform; characterised in that the preform and fibre are rotated relative to each other during the drawing such that the structures in the cladding region of the drawn fibre extend helically along the drawn fibre.

The helical structures may be achieved by any suitable method. It may be that the preform is rotated and the fibre is not rotated. Alternatively, it may be that the fibre is rotated and the preform is not rotated.

Preferably, the preform and fibre are rotated relative to each other sufficiently quickly that the helical structures have a period that is sufficiently short that, in

use, polarisation modes of light guided in the fibre are coupled to each other.

Preferably, the preform and fibre are rotated relative to each other sufficiently quickly that the helical structures break up and become discontinuous along their respective helices. The preform and fibre may be rotated relative to each other in the same sense throughout rotation. Alternatively, the sense of rotation may change during the draw.

Preferably, the fibre is wound onto a drum as it is drawn. The fibre may be rotated by rotating the drum about the axis coincident with the fibre being wound onto it. Alternatively, the fibre may be rotated by rotating a chuck holding the fibre and positioned upstream of the drum. It is possible to achieve higher rotation speeds by using a chuck that is rotated first in one direction and then in the other than by rotating the drum itself.

Preferably, the method comprises the step of propagating an acoustic wave through the fibre and/or preform to enhance break-up of the helical structures into structures that are discontinuous along their respective helices.

Alternatively, the preform and fibre may be rotated relative to each other sufficiently slowly that the helical structures have a period that is sufficiently long that there is substantially no coupling between polarisation modes of the fibre.

Preferably, the preform is formed from a bundle of rods and/or tubes.

Embodiments of the invention will now be described, by way of example only, with reference to the drawings, of which:

Fig. 1 is (a) a side view of a fibre according to the invention, (b) a transverse cross-section through the fibre

at the line A-A′ and (c) a transverse cross-section through the fibre at the line B-B′.

Fig. 2 is a drawing tower for drawing the fibre of Fig. 1.

Fig. 3 is (a) a side view of another fibre according to the invention, (b) a transverse cross-section through the fibre at the line C-C′ and (c) a transverse cross-section through the fibre at the line D-D′.

Fig. 4 is (a) a side view of a fibre according to the invention, (b) a transverse cross-section through the fibre at the line E-E′ and (c) a transverse cross-section through the fibre at the line F-F′.

An example of a fibre 10 according to the invention comprises (Fig. 1) a cladding region 15 and a core region 40, the core region lying along the central longitudinal axis of the fibre 10. The cladding region 15 comprises a plurality of elongate holes 30 embedded in a silica matrix 20 (only six holes 30 are shown in Fig. 1(a), for ease of illustration). Each hole 30 extends in a helix that rotates around the longitudinal axis of the fibre 10. In any transverse cross section (e.g. Figs 1(b) and (c)), holes 30 are arranged in the same position relative to the core 40, but the arrangement rotates gradually along the length of the fibre; thus the arrangement in Fig. 1(c) is rotated by 90 degrees with respect to the arrangement in Fig. 1(b).

The helical structure of the holes is sinusoidal in side view (Fig. 1(a)) and has a period P of 10 cm.

Fibre 10 is drawn on a standard drawing tower 50 of the type used to draw standard telecomms fibre (Fig. 2(a)). Fibre 10 is drawn from preform 60, which has a diameter of about 20 mm and which comprises a bundle of silica canes and silica tubes which are fused together by heating. (The central holes of the tubes form holes 30 in fibre 10.) The drawn fibre 10 has a diameter of about 100 microns. The fibre 10 is drawn in the usual way from preform 60, except

that the preform 60 is spun during drawing to twist holes 30 into their helical structure.

Preform 60 is heated at its end by furnace 70 to soften the silica and a fibre is drawn in the usual way onto a drum 80 that is rotated by a motor at a speed approximately 40000 times faster than the rate at which the preform is fed downwards. Simultaneously, preform 60 is rotated by motor 90 to twist fibre 10 where it is drawn from preform 60. The helical structure sets in fibre 10 as each part of the twist moves away form furnace 70 and cools.

Fibre 10 is a photonic crystal fibre. As a result of the drawing process, in any transverse cross-section, fibre 10 is two-fold rotationally symmetric about core 40. If holes 30 were not helical, fibre 10 would therefore exhibit significant birefringence; that is, there would be a 'fast' axis along which light would see a lowest effective refractive index and a 'slow' axis, orthogonal to the fast axis, along which light would see a highest refractive index. The beat length of that birefringence would be of the order of 1 mm. The helical structure of holes 30 has a period of 10 cm. The period of the helix of holes 30 is therefore very much larger than the beat length of the birefringence. The fast and slow axes therefore rotate with the twisting holes 30 along the length of the fibre; for example, at B-B', the fast and slow axes have rotated by 90 degrees from their position at A-A'.

In an alternative embodiment (Fig. 2(b)), drum 80 is mounted on a rotatable stage 100 and stage 100 is rotated such that the fibre 10 is wound onto the drum 100 at the axis of rotation of stage 100.

In a further alternative embodiment (Fig. 2(c)), rotatable chuck 105 is provided between drum 80 and furnace 70. A helical hole structure is achieved in fibre 10 by rotating chuck 105 alternately in a clockwise and an anti-

clockwise direction. There is no need to rotate drum 80, which enables higher rotation speeds to be achieved.

Another example of a fibre according to the invention, fibre 110 (Fig. 3) again comprises a cladding region 115 and a core region 140, the core region lying along the central longitudinal axis of the fibre 110. The cladding region 115 again comprises a plurality of elongate holes 130 embedded in a silica matrix 120. The fibre is again drawn from a rotating preform and so each hole 130 again extends in a helix that rotates around the longitudinal axis of the fibre 110 and again in any transverse cross section (e.g. Figs. 3(b) and (c)), holes 130 are arranged in the same position relative to the core 140, but the arrangement rotates along the length of the fibre 110. However, in this embodiment, the helical structure of the holes 130 has a much shorter period, being 100 microns, than the period of holes 30 in fibre 10. The shorter period results from fibre 110 being spun at a much higher speed.

The period of holes 130 is thus much shorter than the beat length of the birefringence of the fibre 110 that would result if the fibre 110 had not been spun. Consequently, light propagating in one polarisation mode is coupled into the other polarisation mode and fibre 110 behaves as if it is not birefringent.

Another example of a fibre according to the invention, fibre 210 (Fig. 4) again comprises a cladding region 215 and a core region 240, the core region lying along the central longitudinal axis of the fibre 210. However, in fibre 210, the cladding region 215 comprises a plurality of short bubble-like cavities 230 embedded in a silica matrix 220. Each cavity 230 is again of approximately circular cross-section in a plane transverse to the longitudinal axis of fibre 210 but is of a length that is of a similar order of magnitude to the cavity's diameter. Cavities 230 are arranged along a set of helices that rotate around the

longitudinal axis of the fibre 210. Thus, cavities 230 form discontinuous helices about the fibre axis. In some transverse cross sections (e.g. Fig. 4(b)), cavities 230 are arranged in an arrangement similar to that of holes 30 and 130 and that arrangement again rotates along the fibre as one moves from E-E′ to F-F′. However, there are no parts of cavities 230 visible in some transverse cross-sections (e.g. Fig. 4(c)), as those cross-sectional planes coincide with silica 'gaps' between adjacent cavities in each helix. In this example, the sense of rotation of the helices varies along the fibre, from clockwise to anti-clockwise and back again, repeatedly.

Cavities 230 are formed in fibre 210 using the apparatus of Fig. 2(c). The fibre 210 is rotated by rotation of chuck 105 at a very high speed, alternately clockwise and then anti-clockwise. The holes at the centres of the tubes forming the preform bundle break up into small cavities 230 rather than remaining intact as elongate holes, such as holes 30, 130. The break up of the holes may be encouraged by passing along the preform an acoustic wave of a wavelength similar to the length of cavities 230 desired (i.e. by vibrating the fibre or preform at an appropriate frequency).

The short length of cavities 230 results in stronger coupling between polarisation modes of the fibre 210.